1995

Status of free electron lasers in 1994

Colson, W.B.

Nuclear Instruments and Methods in Physics Research A, Volume 358, (1995), pp. 532-535

http://hdl.handle.net/10945/44054

Nuclear Instruments and Methods in Physics Research A 358 (1995) 532–535

NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

ELSEVIER

Status of free electron lasers in 1994

W.B. Colson *

Physics Department, Naval Postgraduate School, Monterey, California 93943, USA

Abstract

Eighteen years after the first operation of the short wavelength free electron laser (FEL) at Stanford University, there have been many significant accomplishments. FEL research in the infrared, visible, ultraviolet, and X-ray wavelength regimes is discussed.

1. Historical perspective

The first sources of powerful coherent radiation were the radar and microwave electron tubes invented earlier this century. Even today, these tubes remain as the most successful and useful sources of coherent radiation, with wavelengths ranging from several meters down to about a millimeter. Electron tubes are known to be inexpensive, compact, reliable, efficient, and powerful. There is some justification for believing that this is the "right" way to generate coherent radiation. A particular microwave tube developed in 1960 by Phillips, called the Ubitron [1], was quite similar to the free electron laser in design and operation. The invention of the open resonator by Schawlow and Townes in 1958 [2] led to the development of the conventional atomic laser. The atomic laser has become successful in many scientific and commercial applications. Several limitations of the conventional laser, such as the lack of continuous tunability and breakdown at high power densities, are due to the use of excited electrons bound to atoms. The goal of the free electron laser (FEL), invented by Madey, is to extend the success of the microwave tube from millimeter to nanometer wavelengths [3–5].

2. FEL attributes in 1994

Most FEL attributes have been known for some time, but their status deserves a review in 1994. References and a table of experiments describing the topics found below can be found in these proceedings.

* Tel. +1 408 656 2896, fax +1 408 656 2834, e-mail colson@physics.nps.navy.mil.

Continuous tunability: One of the most important and most often quoted FEL attributes is continuous tunability. The resonance condition depends on the electron velocity component along the undulator axis. At resonance, one wavelength of light passes over an electron as the electron passes through one undulator wavelength. The operating wavelength is typically varied on a slow time-scale by changing the undulator gap to control the undulator field strength and the electron z velocity, or on a fast time-scale by changing the electron beam energy. FEL facilities like CLIO (France), FOM (The Netherlands), Stanford, Vanderbilt, Duke, and UC Santa Barbara routinely provide tunable radiation to users. At many facilities today, the user can control the FEL wavelength from within his experimental laboratory space. The Stanford FEL controls the operating wavelength by varying the electron beam energy with a feedback system designed to hold the wavelength fixed at a wavelength of the user's choice.

Reliable operation: Microwave and RF electron tubes, medical linear accelerators, synchrotron light sources, storage rings and electrostatic accelerators all have proven to be reliable systems. The FEL is based on the same technology and could be expected to have similar reliability. The FEL facilities mentioned above have been providing over 2000 user hours of beam-time per year, limited largely by operating budgets.

Flexible micropulse and macropulse structure: The FEL optical pulse structure is determined by the longitudinal micropulse and macropulse structure of the electron beam. An FEL using a recirculating electrostatic accelerator can produce a CW or nearly CW beam for narrow band applications. An FEL driven by a RF linac can take advantage of the mature RF technology of linear accelerators used to manipulate and control the electron beam and thus the optical beam. The micropulses can be injected at frequencies up to the RF frequency. The micropulse length

SSDI 0168-9002(94)01547-3

can also be controlled by as much as a factor of ten over short time-scales. The FEL driven by a linac can produce micropulses which are locked to an external clock with sub-picosecond jitter. The FEL can also operate "simultaneously" at independently controlled wavelengths, providing for multiple color experiments. Similar tricks can be played with chirped micropulses, but on a picosecond time-scale. The longitudinal coherence is generally transform limited, except for FELs with extremely long pulses. In the infrared, the facilities at CLIO and Stanford can now produce micropulses that are less than a picosecond in length.

Operation in higher harmonics: If the undulator field is sufficiently strong, the FEL emits radiation in several higher frequency harmonics. Many FELs have a sufficiently strong undulator that there is significant power and gain in the higher harmonics. The gain and coherent emission into higher harmonics has been observed on several experiments. BNL and SLAC propose using higher harmonics to reach short UV or X-ray wavelengths. The APEX FEL at LANL has lased on the 3rd harmonic to produce ultraviolet light using a relatively low energy electron beam.

Control of fundamental interaction: The spontaneous emission bandwidth and the gain bandwidth can be as easily controlled in the FEL as in microwave tubes. A tapered undulator can significantly increase extraction efficiency and extend the saturation limit in the FEL by increasing gain in strong optical fields. In the klystron undulator, a dispersive magnet can be introduced in the middle of the undulator to increase gain in weak optical fields. The tapered or klystron undulator are examples of how the FEL undulator can be designed to alter the FEL interaction characteristics. Both have been demonstrated in experiments. About 10 years ago, research on the tapered undulator dominated, but now only the conventional and klystron undulators are being pursued.

Ideal lasing medium: The lasing medium of the FEL contains only relativistic electrons, the static undulator magnetic field, and the laser light in vacuum. Energy is "pumped" into the interaction volume at the speed of light, the gain medium cannot be damaged during high power operation, the amplifying medium is transparent to all wavelengths, and the waste heat is removed at the speed of light. The FEL has the potential for high peak power (GWs has been demonstrated), and high average power of several MWs should be possible. This is another advantage that is shared between the FEL and the high-power microwave tube.

Single transverse mode: A high density electron beam allows the formation of a single, diffraction limited, transverse optical mode. A fundamental optical mode in the visible with a Rayleigh length of one to a few meters yields an optical mode waist that is just a bit larger than a typical relativistic electric beam. Industrial applications at CEBAF require high beam quality as do long-range military and power-beaming applications, such as the SELENE Project at the Naval Air Warfare Center, China Lake, CA.

Flexible polarization: The undulator polarization, linear or circular, determines the polarization of the laser light. Both types of FEL have been used successfully. Variable elliptical polarization can be achieved by using a specially designed undulator. This kind of undulator could be useful at a user facility where it may not be possible to use rotating optical components. At present, only the linear and helical undulators are in use.

Theoretically predictable: Theory continues to play an important role in the progress of FEL technology and concepts. Agreement between theory and experiment is excellent when the experimental parameters are correctly described. The design of proposed FELs is preceded with extensive analytical and numerical calculations. Since many new FELs proposed in new wavelength ranges would cost tens of millions of dollars, simulations are crucial to the design. The same theoretical formalism works from cm wavelengths to 0.1 nm wavelengths, and only depends on the FEL design, the electron mass m, the electron charge magnitude e, and the speed of light c. Nearly every major FEL laboratory has extensive simulation capability.

3. Exciting new directions in 1994

Some of the FEL's attributes have led to particularly exciting new directions. As these proposed directions develop, the next few years may become the most important in FEL history.

Far-infrared (FIR) wavelength range operation: Possibly the most significant FEL attribute is that it can be designed to operate in wavelength ranges not accessible by other sources. For wavelengths shorter than 500 μm, there is little competition from microwave tubes, and for wavelengths longer than 10 μm, there is little or no competition from conventional lasers. Several FEL facilities, CLIO, Stanford, Vanderbilt, Duke, UCSB and FOM, can operate in part of this range now, and are expanding their coverage. Most (except UCSB) also provide picosecond pulses for new scientific experiments in this wavelength range.

Reducing FEL size and cost: One of the most exciting aspects of the FIR FEL is that it is the lowest cost, smallest size, and lowest risk FEL to build. These critical issues have seriously impaired FEL development over the last 20 years. A FIR FEL is potentially a laboratory device costing under one million dollars and can be a facility that resides in individual departments of a major university, much like an electron microscope. Grumman and LANL are working on small laboratory scale FELs for a facility of this size now. Professor R. Pantell (Stanford) reports that he has just developed a FIR FEL for under 300K dollars that can be built and operated by graduate students. This will provide scientists with an FEL that fits in their own laboratory, and makes FEL research much less expensive.

UV wavelength range operation: The FEL in Novosibirsk has already reached a wavelength of 240 nm and other FELs are expected to soon operate below 100 nm. The FEL increases optical brightness and coherence by many orders of magnitude compared to a synchrotron source. The key technology required for the short-wavelength FEL is a high quality electron beam, and the necessary characteristics for UV operation have already been demonstrated. It is not a big stretch for the FEL to reach UV wavelengths. The FEL has a decided advantage at short wavelengths compared to the conventional laser. The FEL electron beam does not spontaneously emit in vacuum, so electrons remain in a given state until the beam enters the undulator. At present, a UV FEL appears to be a large laboratory machine costing tens of millions of dollars, with a reasonably high level of confidence for achieving expected goals. Further research should be used to explore reducing the cost, size, and residual risk of UV FELs. To reach the UV, BNL plans to explore higher harmonics, Duke University will use a high-energy storage ring, and LANL proposes to use a micro-undulator.

X-ray wavelength range operation: It has long been realized that the FEL may become the first true X-ray laser. In the 1 nm wavelength range, there are no available mirrors. With no mirrors, self-amplified spontaneous emission (SASE) would be used in a long undulator to develop coherent laser light from spontaneous emission in a single pass through the undulator. A proposal to use part of the SLAC accelerator would achieve about a GW of radiation power in a short pulse of about 200 fs with peak brightness and peak coherent power many orders of magnitude higher than third generation light sources. The electron beam energy would be about 10 GeV with peak beam current of 2500 A to 5000 A. The development of the RF photocathode electron gun, emittance preservation, electron pulse compression techniques, and a long, precise 50 m undulator are key factors in the development. Much of the required electron beam properties have been demonstrated at the Los Alamos National Laboratory and the Stanford Linear Collider. Harmonic emission may be used to reach even shorter wavelengths near 0.1 nm. The increased radiation brightness may result in sample damage that requires innovation by the experimenter. X-ray FEL development should be preceded by significant research in order to reduce risk, and cost.

It is worth mentioning that Vanderbilt plans to use backscattered X-rays from the infrared FEL to generate incoherent 20 keV photons for users. At NRL, a lower energy electron beam and a high peak power laser will be used to demonstrate the fundamental process.

High-power, efficient operation: The FEL has the potential for high power operation. The FEL has an advantage over the high power (MW) gyrotron at 1 mm and shorter wavelengths, because of the large interaction volume and the ability to dissipate heat. Since the FEL is based on the same principles as the microwave electron tube, it has the potential of high efficiency. The FEL wall-plug efficiency is improved by recirculating the electron beam after each pass through the undulator. It has been estimated that the wall-plug efficiency in a superconducting RF FEL with electron beam recovery might reach several tens of percent.

There are several possible applications of a high-average power FEL. FOM (The Netherlands) is building a 1 MW, mm wave FEL for plasma heating and diagnostics. Industrial processing is being explored at CEBAF in collaboration with Dupont and other industrial partners. An FEL has been designed at CEBAF to produce 100 kW of UV power at 350 nm wavelength with a recirculating superconducting linac. A serious effort toward industrial applications is a new direction for FEL development that should prove extremely important.

The U.S. Navy needs to develop a better defense against sea-skimming missiles launched from a nearby shore. One possibility is a MW laser at about 3 μm wavelength which would focus power onto a missile surface to reach, or exceed, 2 kW/cm^2 intensity for a 1 s duration. The engagement would only last about 10 s in order to defend the ship out to a range of about 10 km. This is far less ambitious than the SDIO scenario for missile defense. Boeing, Northrup, LANL, and Rocketdyne are pursuing research programs on high-power FELs for military applications.

The Naval Air Warfare Center (China Lake, CA), NASA, Duke University, the Naval Postgraduate School, and the FEL Group at Novosibirsk, Russia are studying the use of a high-power FEL for powering satellites and other space vehicles.

The Stanford FIREFLY FEL and the LANL Advanced FEL provide opportunities for achieving 1 kW average power demonstrations at relatively low cost. In each case, an existing FEL could be upgraded at a cost of about one million dollars, and would increase the FEL record for high average power from 10 W to 1 kW. This is an important and easily achievable goal for the FEL.

National Research Council FEL Committee Report: The National Research Council has been asked by the Department of Energy to study the scientific opportunities presented by FELs and other advanced coherent light sources. The report [6] results were described by the chairman of the committee, Dr. Don Levy, at this Free Electron Laser Conference. The committee's report recommends (i) building a user facility using a FIR FEL with picosecond pulses, (ii) supporting the development of technology for a vacuum ultraviolet FEL, and (iii) supporting the research and development necessary for an X-ray FEL. One of the important goals of this research and development should be to lower the cost of the FELs. In addition, the report states that a variety of communities potentially benefit from the type of research that will be necessary to produce scientifically useful FELs. It also states that the development of FELs is of interest for applications other than scientific research, for example, industrial, defense, and medical applications. The committee recommendations may lead to a significant national program supporting the development of FELs for scientific applications.

Acknowledgements

The author is grateful for support of this work by the Naval Postgraduate School, Stanford University (N00014-91-C-0170), and SURA/CEBAF.

References

[1] R.M. Phillips, IRE Trans. Electron Devices 7 (1960) 231.
[2] A.L. Schawlow and C.H. Townes, Phys. Rev. 112 (1958) 1940.
[3] J.M.J. Madey, J. Appl. Phys. 42 (1971) 1906.
[4] L.R. Elias, W.M. Fairbank, J.M.J. Madey, H.A. Schwettman and T.I. Smith, Phys. Rev. Lett. 36 (1976) 717.
[5] D.A.G. Deacon, L.R. Elias, J.M.J. Madey, G.J. Ramian, H.A. Schwettman and T.I. Smith, Phys. Rev. Lett. 38 (1977) 892.
[6] Free Electron Lasers and Other Advanced Sources of Light (National Academy Press, Washington, DC, 1994).